Available online at www.sciencedirect.com
SCIENCE DIRECT®
Geoderma 130 (2006) 284–298
GEODERMA
www.elsevier.com/locate/geoderma

Prescribed burning effects on soil physical properties and soil water repellency in a steep chaparral watershed, southern California, USA

K.R. Hubbert[a,*], H.K. Preisler[b], P.M. Wohlgemuth[a], R.C. Graham[c], M.G. Narog[a]

[a] *USDA Forest Service, Pacific Southwest Research Station, Riverside, CA 92507, United States*
[b] *USDA Forest Service, Albany, CA, United States*
[c] *Department of Soil and Environmental Sciences, University of California, Riverside, CA 92521, United States*

Received 21 August 2003; received in revised form 12 January 2005; accepted 1 February 2005
Available online 19 March 2005

Abstract

Chaparral watersheds associated with Mediterranean-type climate are distributed over five regions of the world. Because brushland soils are often shallow with low water holding capacities, and are on slopes prone to erosion, disturbances such as fire can adversely affect their physical properties. Fire can also increase the spatial coverage of soil water repellency, reducing infiltration, and, in turn, increasing overland flow and subsequent erosion. We studied the impacts of fire on soil properties by collecting data before and after a prescribed burn conducted during Spring 2001 on the San Dimas Experimental Forest, southern California. The fire removed the litter layer and destroyed the weak surface soil structure; leaving a thin band of ash and char on top of, and mixed in with, an unstable, granular soil of loose consistency. Median litter thickness and clay content were significantly decreased after fire while soil bulk density increased. At 7 d post-fire, soil surface repellency in the watershed was significantly higher than prior to the burn. At 76 d post-fire, surface soil water repellency was returning to near pre-fire values. At the 2 and 4 cm depths, 7 d post-fire soil repellency was also significantly higher than pre-fire, however, conditions at 76 d post-fire were similar to pre-fire values. Variability in soil water repellency between replicates within a given 15×15 cm site was as large as the variability seen between sites over the 1.28 ha watershed. The increase in post-fire persistence of water repellency was largest beneath ceanothus (*Ceanothus crassifolius*) as compared to a small increase beneath chamise (*Adenostoma fasciculatum*). However, pre-fire persistence was higher under chamise than for ceanothus. Post-fire changes to soil properties may increase the watershed hydrologic response, however the mosaic distribution of water repellency may lead to a less severe increase in hydrologic response than might be expected for a spatially more homogenous increase in repellency.

Keywords: Chaparral; Prescribed fire; Soil properties; Water infiltration models; Water repellency

1. Introduction

Sclerophyll forest biomes (chaparral), associated with Mediterranean-type climate, are distributed over

* Corresponding author. Hubbert & Associates, 21610 Ramona Ave., Apple Valley CA 92307, United States. Tel.: +1 760 961 8349.
E-mail address: huboutwest@earthlink.net (K.R. Hubbert).

0016-7061/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.geoderma.2005.02.001

five regions of the world including parts of California, central Chile, South Africa, western and south Australia and the Mediterranean Basin. Because of a history of fire suppression in southern California, fuel loads of decadent chaparral stands have increased, and are threatening the rapidly expanding urban interface (Keeley et al., 2000). Prescribed burning is the preferred method to reduce these fuels and reduce the fire danger.

Fires greatly alter the physical characteristics of these landscapes. During burning, plant cover and litter layers are consumed, and the mineral soil is heated, resulting in changes to soil bulk density, porosity, texture, color, moisture content, and permeability. Most of the heat from a fire is directed upward, but substantial temperatures at the soil surface can be achieved due to fuel load and residence time. Heating and soil alteration can be significant if the fire residence time is long, or a thin, dry litter layer is completely incinerated (Wells et al., 1979).

Soil water repellency is particularly common in unburned chaparral communities, due in part to the shallow, coarse-textured soils, dry Mediterranean climates, and the high resin content of the organic litter (DeBano, 1981). Most fires create a mosaic of low-, moderate-, and high-severity burn areas because of the non-uniformity of fire temperature and duration; terrain slope and aspect; litter depth and moisture content; species type and distribution; live and dead fuels ratios; fuel densities and moisture contents; and differences in soil moisture and soil texture. Therefore, one should not expect the spatial distribution of soil water repellency to be uniform across a broad landscape, or even at smaller scales in steep watersheds (Robichaud and Miller, 1999).

Because shrubland soils are often shallow with low water holding capacities, and are on slopes prone to erosion, disturbances such as fire can adversely affect their physical properties and hydrologic response. The nature of post-fire hydrologic response and subsequent erosion is, in part, dependent on changes in soil physical properties and the depth and spatial variability of the soil water repellency (Ritsema and Dekker, 1994). Mosaic distribution of water repellency may lead to a less severe increase in hydrologic response than might be expected for a spatially more homogenous increase in repellency. Consequently, it is important that land managers understand post-fire watershed response when prescribing post-fire erosion control treatments. Our objectives in this study were (1) to gather information about fire impacts on soil properties, (2) to determine the pre- and post-fire spatial and temporal variability of soil water repellency in steep chaparral, and (3) to investigate how selected soil properties and different plant species affect the distribution of soil water repellency on the landscape.

2. Materials and methods

2.1. Site description

The 1.28 ha study watershed (34°12′45″ N, 117°45′30″ W) is located in the San Dimas Experimental Forest (SDEF) in the foothills of the San Gabriel Mountains of southern California, approximately 45 km northeast of Los Angeles, California. Elevation of the watershed ranges from 820 to 990 m. Topography is rough, characterized by precipitous canyons, deeply cut channels, and steep slopes ranging to 75% (>90% exceeding 55%) (Ryan, 1991; Nourse, 1998). The climate is Mediterranean, with hot, dry summers and cool, wet winters. Mean annual precipitation is 678 mm (Dunn et al., 1988).

2.2. Geology, soils, and vegetation

Much of the rock in the watershed is Pre-Cambrian to Mesozoic strongly banded and foliated gneisses and schists mixed with a large percentage of igneous dike rocks (Story, 1948; Nourse, 1998). Bedrock in the area has been subjected to intense heat and pressure resulting in a high degree of alteration, faulting, folding, and fracturing. As a result, the rocks are poorly consolidated and very unstable (Sinclair, 1953). The soils are usually shallow and coarse-textured, with rock-fragments throughout (Graham et al., 1988). Soil material on these slopes moves too frequently to allow strong development of soil horizons. Soils mapped in the general area of the study site are of the Trigo series (loamy, mixed, nonacid, thermic, shallow Typic Xerorthents) (Ryan, 1991).

The natural vegetation is chaparral, characterized by sclerophyllous leaves, 1–3 m plant height, and dense canopies (Hanes, 1974). Common chaparral species found at the study site include: chamise (*Adenostoma* *fasciculatum* Hook and Arn.), hoaryleaf ceanothus (*Ceanothus crassifolius* Torr.), Eastwood manzanita (*Arctostaphylos glandulosa* Eastw.), sugar bush (*Rhus ovata* S. Watson), scrub oak (*Quercus berberidifolia* Liebm.), black sage (*Salvia mellifera* E. Greene), and wild buckwheat (*Eriogonum fasciculatum* Benth.). The stand age of the chaparral was 41 years, with the watershed last burning during the 1960 Johnstone Fire that consumed 88% of the 6947 ha forest.

2.3. Field and laboratory measurements

The study watershed was burned on May 15, 2001, ignited by flaming gel applied by a helicopter. The prescribed fire, part of a larger prescribed burn conducted for 2 d in the SDEF, burned for 1–3 h in the target watershed. Burn severity was estimated qualitatively from post-fire fuel size diameter (chamise branches), color of ash, and degree of litter consumption (Wells et al., 1979; Miller, 2001).

Morphological descriptions, based on auger holes and soil pits, were developed for the soil and underlying weathered bedrock (Soil Survey Division Staff, 1993; Schoeneberger et al., 1998) (Table 1). For representative soil descriptions, we chose interfluve positions between swales on 55–60% sideslopes within the watershed.

To determine particle size distribution, bulk density, water content, water repellency, and litter depth, eight transects, roughly spaced to encompass the watershed from top to bottom, crossed the watershed

Table 1
Selected pre-and post-fire morphological properties of the soil and weathered bedrock on E-and W-facing aspects

Horizon	Depth (cm)	Dry color	Moist color	Texture[a]	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Structure[b]	Consistence		Roots[c]	Boundary[d]
										Dry[e]	Moist[e]		
Post-fire site 1. Aspect W, slope 62% (28°) coarse, loamy, mixed, thermic Typic Xerorthents													
Oi	2–0	(post-burn ash layer)											
A1	0–5	10YR4/2	10YR3/1	GRls	18.6	79.6	15.8	4.6	gr	L	L	1vf	A,S
AC	5–12	10YR5/3	10YR4/3	GRls	21.2	83.7	14.2	2.1	gr	S-SH	VFR	1vf	A,W
Cr1	12–18	7.5YR 6/4	7.5YR 4/4						rock str.	HA	FI	1f	A,W
Cr2	18–34	7.5YR 6/4	7.5YR 4/4						rock str.	HA	VFI	2f	G,W
Cr3	34–69	ND[f]	ND						rock str.	HA	VFI	1co, 1vc	G,I
R	69+												
Post-fire site 2. Aspect E, slope 71% (32°)													
Oi	1–0	(post-burn ash layer)											
A	0–7	10YR5/2	10YR3/2	GRls	25.7	84.7	14.0	1.3	1bk	L	L	1vf	A,W
C/Cr	7–15	10YR5/4	10YR3/2	GRs	22.4	89.1	9.9	1.0	gr	SH	VFR	1f	G,W
Cr1	15–45	10YR4/3	10YR4/3						rock str.	MH	FR	1m	G,W
Cr2	45–115	10YR5/4	10YR3/3						rock str.	MH	FI	2co, 1vc	G,I
R	115+												
Pre-fire site 1. Aspect W, slope 62% (28°)													
Oi	2–0	(chamise and ceanothus litter)											
A1	0–1	10YR4/3	10YR3/2	GRls	15.1	79.1	15.3	5.6	1pl	S	VFR	1vf, 1f	A,S
A2	1–5	10YR5/3	10YR3/2	GRls	20.4	80.6	15.2	4.2	1bk	S	VFR	2vf	A,W
AC	5–12	10YR5/3	10YR4/3	GRls	20.1	84.8	12.9	2.3	gr	S-SH	VFR	1vf	A,W
Pre-fire site 2. Aspect E, slope 71% (32°)													
Oi	1–0	(chamise and ceanothus litter)											
A	0–7	10YR5/4	10YR3/4	GRls	21.8	85.1	11.0	3.9	1bk	S	VFR	1vf,1f	A,W

[a] GR=gravelly, ls=loamy sand, s=sand.
[b] 1=weak; pl=platy, gr=granular; bk=angular blocky, rock str.
[c] 1=few; 2=common; vf=very fine (<1 mm); f=fine (1–2 mm); m=medium (2–5 mm); co=coarse (>5 mm); vc=very coarse.
[d] A=abrupt; G=gradual; S=smooth; W=wavy; I=irregular.
[e] S=soft, SH=slightly hard, FR=friable, L=loose, HA=hard, VFR=very friable, FI=firm, VFI=very firm, MH=moderately hard.
[f] ND=not determined.

in a chevron pattern perpendicular to the main channel. Six to eight sample locations were randomly chosen along each transect, resulting in a total of 54 sampling sites. An additional 51 sites were selected randomly between transects. Particle size distribution was determined for the mineral soil by the pipette method using samples that were sieved to remove coarse fragments greater than 2 mm in diameter (Gee and Bauder, 1986). The A horizon bulk density was determined by the hollow-core method (Blake and Hartge, 1986), using a sampler that took a 5.1 cm long core with a diameter of 7.3 cm that yielded a volume of 212.8 cm^3. Subsequent determinations of the volume and mass of rock-fragments greater than 2 mm were subtracted to yield a corrected bulk density (Soil Survey Laboratory Staff, 1992; Vincent and Chadwick, 1994). Porosity was calculated from bulk density assuming a particle density of 2.65 g cm^{-3} (Danielson and Sutherland, 1986). Water content measurements were made gravimetrically on soil samples taken from the A horizon at the 0–5 cm depth (Gardner, 1986).

At each sampling point, soil water repellency was determined by noting the water drop penetration time (WDPT) (Krammes and DeBano, 1965). Sampling was conducted pre-fire, 7 d post-fire, and 76 d post-fire. Twenty drops from a squeeze bottle were applied at the mineral soil surface within a 15×15 cm area. Another 20 measurements were taken at 2 cm depth and 10 measurements at the 4 cm depth. The time of water drop penetration was determined when the droplet changed from convex to flat, and infiltrated. By taking measurements at (1) intersite (mesoscale) locations along transects and 2) intrasite (microscale) locations within 15×15 cm squares, variability was assessed at two spatial scales (Doerr et al., 1998). We modified existing soil water repellency indexes (DeBano, 1981; Dekker and Ritsema, 2000) to give us the following classification scheme: 0–1 s—not repellent, 1–5 s—very low repellency, 5–30 s—low repellency, 30–180 s—moderate repellency, and >180 s—extreme repellency.

Pre-fire litter depths were measured at the four corners and one mid-point of a 50×50 cm square placed at the 54 transect-sampling sites. Post-fire litter reduction was determined using steel duff pins (20 cm in length) that were installed flush with the litter surface at the same pre-fire litter sites. After the burn, the distance of the head of the pin protruding above the mineral soil was measured to determine litter consumption.

For plant measurements, each slope was divided into 4 equal segments along the eight pre-established transects. Within each segment, a random number, originating from the beginning of the segment, was chosen to represent a sampling point. Measurements were collected on the closest plant to the point. These included: species identification, plant cover, plant height, and stem tip diameter. Plant cover measurements were taken using a meter tape at N to S, and E to W coordinates relative to the individual plant.

2.4. Statistical model and estimation

We derived a stochastic model (Appendix 1) describing relationships between selected soil characteristics and water repellency in terms of physically meaningful parameters. The parameters of the system correspond to those in Philip's equation for water infiltration (Philip, 1969). An approximation of Philips equation for the initial phase of water infiltration is $\mu=\lambda\tau$, where μ stands for the cumulative rate of infiltration, or equivalently, the breakdown in water repellency; λ is the sorptivity, or rate of breakdown in repellency; and the unit of time, τ, is $t^{0.5}$. In our model we assumed τ to be an unknown function of time and estimated the functional form from the data. The rate parameter, λ, was assumed to be a function of location. The latter enables us to study the simultaneous effects of selected soil properties at a specific location on the rate of breakdown in repellency. Breakdown of water repellency corresponds to the time at which the water drop loses its spherical state and infiltrates into the soil. The model developed in Appendix 1 is based on a latent (hidden) variable, because direct observation on the cumulative infiltration rate over time is not possible because infiltration is too fast. We used the generalized additive model gam in S-plus (Cleveland et al., 1992; S-PLUS, 2001) to obtain estimates of the simultaneous effects of site characteristics and time on soil sorptivity. The potential correlation between responses at nearby sites was incorporated in the model by including a smooth function of the location coordinates in the linear predictor (Kaluzny, 1997). We used the likelihood ratio test to assess the significance of the explanatory variables (Lehman, 1959).

3. Results and discussion

3.1. Prescribed burn

The prescribed burn consumed the chaparral vegetation in a period of less than 30 min leaving only charred plant skeletons, charred litter, black ash and bare soil conditions. Much of the ash was either blown off-site or redistributed on the hillslopes by strong “Santa Ana” (foehn winds) that occurred 2 weeks after the fire. Chamise fuel tip diameters were similar throughout the watershed (mean fuel tip diameters were <6 mm) indicating light burn severity in the aboveground foliage (Wells et al., 1979). Ground fuels continued to smolder for 1–3 h, increasing the duration and severity of the fire to the ground surface. However, the heat pulse did not penetrate deeply into the soil and damage lignotuber tissues, as evidenced by the vigorous post-fire resprouting of most of the chaparral species. As noted by Hellmers et al. (1955), most chaparral species root deeply, anchoring in bedrock fractures to depths of 5–9 m.

3.2. General plant and soil properties, pre-and post-fire

Pre-fire canopy covers were 31% (SD = 0.40) for chamise, 28% (SD = 0.36) for ceanothus, 17% (SD = 0.20) for sugar bush, 5% (SD = 0.07) for scrub oak, and 3% (SD = 0.03) for manzanita. About 15% of the cover (SD = 0.02) was bare ground, rock outcrops, and other plant species. Average litter depth before fire was most shallow beneath manzanita (19 mm, SD = 14) and chamise (19 mm, SD = 27), and deepest beneath scrub oak (54 mm, SD = 24), ceanothus (55 mm, SD = 62), and sugar bush (69 mm, SD = 36). A study by Kittredge (1955) found that scrub oak and sugar bush had average litter levels of 33.4 t ha^{-1}, whereas chamise had only 5.7 t ha^{-1}. Beneath scrub oak and sugar bush, fungal hyphae mats up to ~50 mm in thickness and >6 m^2 were observed at the mineral soil/litter interface. Fire reduced the median litter depth for the watershed from 22 to 3 mm (Fig. 1). Areas where litter was not completely consumed by fire emerged as an amalgamation of unburned litter, ash, char, and, loose mineral soil. In steep chaparral, litter helps maintain high soil infiltration rates, reduces soil evaporation, and protects soil from high solar temperatures that can damage buried rootstocks (lignotubers) or buried seeds, which provide rapid regeneration after fire (Keeley and Keeley, 1987).

The soils were coarse-loamy, mixed, thermic Typic Xerorthents (Table 1). Average depth of soil to weathered bedrock for the watershed was 25 cm (SD = 10) situated on slopes averaging 68%. Surface horizons had gravelly loamy sand textures and were soft and very friable (Table 1). Highly weathered bedrock was exposed at the surface in many locations, providing rock material >2mm to the slopes. On very steep slopes in this region, soils appear to be in continual movement due to gravity and wind, especially during dry periods (Radtke, 1981). During the fire, cones of dry ravel were deposited along the main drainage of the watershed. Post-fire covering of litter pins by soil material and increases in gravel content of the surface soil (Fig. 1) provided further evidence that soil materials moved downslope during the fire when barriers such as litter, downed limbs, shrub boles, or low spreading branches were consumed.

The prescribed burn removed most of the litter layer and destroyed the pre-fire thin platy structure of the A horizon resulting in a post-fire granular structure at the surface (Table 1). Loss of surface structure resulted in a change from soft (pre-fire) to loose (post-fire) consistency (Table 1). What little structure observed in the A horizon pre-fire is believed to be a result of a slight increase in stability due to fungal growth between the soil and litter layers. Fungal mycelia can surround and intertwine the soil particles and thus form very stable aggregates (Dunn et al., 1982).

3.3. Particle size distribution, soil bulk density, porosity, and water content

Following the fire, there was no significant post-fire change in the sand or silt fractions, but the clay fraction exhibited a significant 39% reduction from 5.4% to 3.1% (Fig. 1). The decrease in the clay

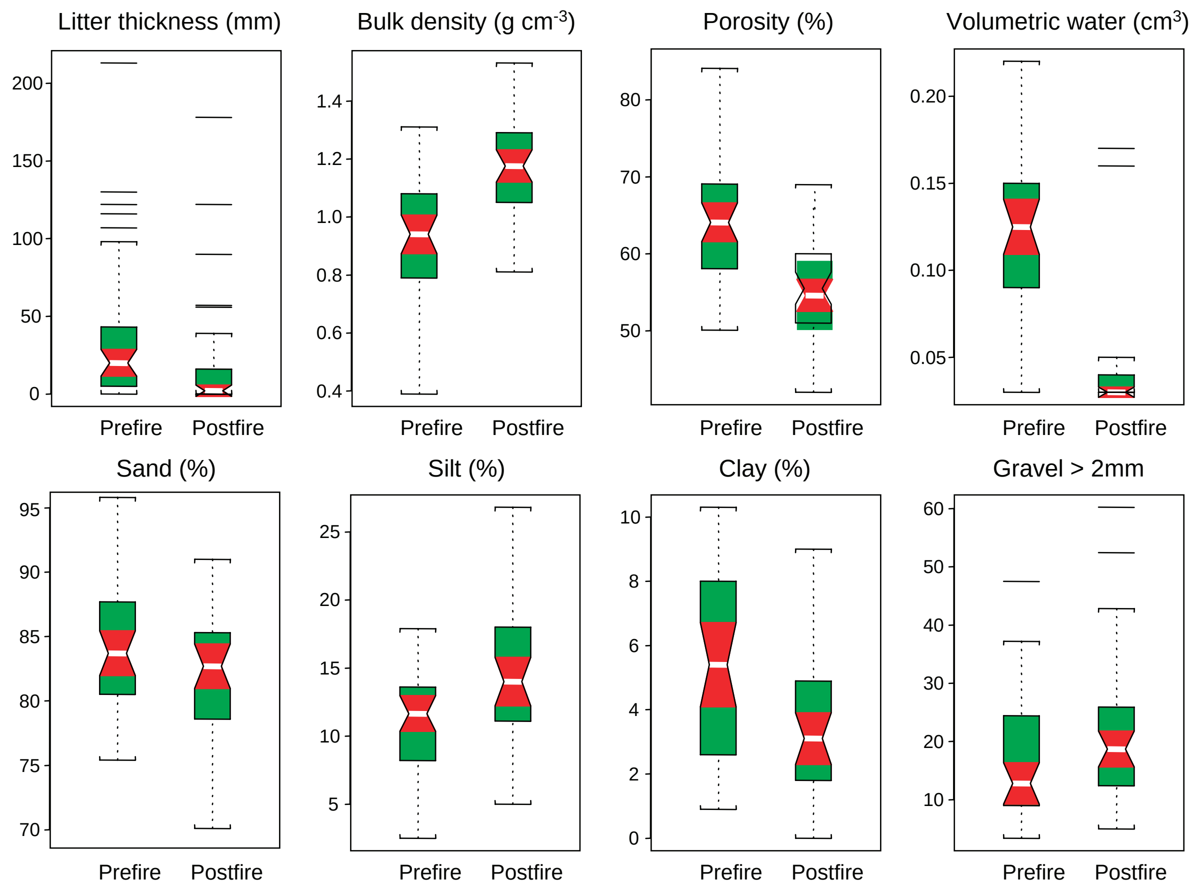

Fig. 1. Box plots describing pre- and post-fire values of the following soil properties: soil bulk density at 0–5 cm depth (g cm^{-3}), percent sand, silt, and clay at 0–5 cm depth, litter thickness, percent soil porosity at 0–5 cm depth, percent gravels greater than 2 mm, and soil volumetric water content at 0–5 cm depth (cm^{3} cm^{-3}). White bar in middle of box represents the median. Notched part of the box represents the approximate 95% confidence band. The confidence intervals are for the individual medians. Middle 50% of data are within the darker shaded boxes. Brackets outside boxes represent the range without outliers included. Outliers are straight lines shown outside the range. Where darkened notches do not overlap, values are significant.

fraction suggested that there was some aggregation of finer particles into larger silt-size particles. In a study where black ash was also observed, Ulery and Graham (1993) reported a decrease in clay content from 13.0% unburned to 11.8% burned. In addition, reduction of the clay fraction by burning may have resulted in soils on the steep slopes becoming less stable due to the cohesive influence of the clays being decreased (Duriscoe and Wells, 1982). The unusual but relatively small decline in the sand fraction may have involved experimental error. Median values for gravel material >2 mm increased from 12.8% pre-fire to 18.7% post-fire (Fig. 1), a result likely related to the release of trapped >2 mm material from the overlying litter layers during the fire, which ultimately intermixed with the disturbed surface soil.

After the fire, median soil bulk density at the 0–5 cm depth increased significantly by 26% from 0.94 g cm^{-3} pre-fire to 1.18 g cm^{-3}, with a corresponding decrease in porosity (Fig. 1). It appears that the destruction of soil aggregation, and the loss of organic matter, contributed to the increase in bulk density (Giovannini et al., 1988). Welling et al. (1984) reported an increase in bulk density and loss of infiltration when fungal mycelia were eliminated by fire.

Moisture content within the 0–5 cm depth was reduced from a mean of 0.13–0.03 $cm^3\ cm^{-3}$ after the burn (Fig. 1). The wettest spots pre-fire were beneath a ceanothus which exhibited the high pre-fire mean litter depths of 55 mm. Fire probably evaporated most of the water in the near soil surface, but evapotranspiration likely accounted for some of the moisture reduction at 2–5 cm between the time of pre-fire sampling and sampling following the burn. DeBano et al. (1979) reported a moisture decrease of 80% from 20.1 $cm^3\ cm^{-3}$ pre-fire to 4.1 $cm^3\ cm^{-3}$ post-fire at a soil depth of 0–1 cm beneath chaparral vegetation.

In section 2.6 we described how the WDPT data may be used to estimate two parameters of the system: 1) τ, the unit of time; 2) λ, the sorptivity of the soil. The estimated function for τ was approximately linear when plotted against square root of time. This is consistent with Philip's equation of water repellency. The estimated effect of depth and fire period on the sorptivity parameter, λ, is presented in Fig. 2. Pre-fire sorptivity levels appeared to be highest at 4 cm depth. Seven days after fire sorptivity levels were significantly lower at all depths compared to the pre-fire levels. Seventy-six days after fire there was some indication of the soil sorptivity at the surface returning to levels seen before the burn, however at 4 cm the sorptivity appeared to be decreasing.

3.4. Pre-fire soil water repellency and spatial variability

Fuels in the 41-year-old mixed chaparral watershed were dense and almost impenetrable on foot, having not burned since the 1960 Johnstone Fire. Prior to the burn, 41% of the 1.28 ha watershed soil surface exhibited "very low to no repellency", 22% "low repellency", and 37% "moderate to extreme repellency" (Fig. 3). A survey conducted by Krammes and DeBano (1965) on the SDEF reported that at least 60% of the soils there could be classified as water repellent. The pre-fire repellency numbers presented here for the surface soil can be considered an approximate soil background level for a 40-year-period absent of fire. As discussed by Teramura (1980), many of the hydrophobic compounds are released by decomposition and leaching of chaparral vegetation and litter during the period between fires.

"Not repellent", "very low", and "low repellency" totaled 53% at the 2 cm depth pre-fire, while "moderate" to "extreme repellency" totaled 33%

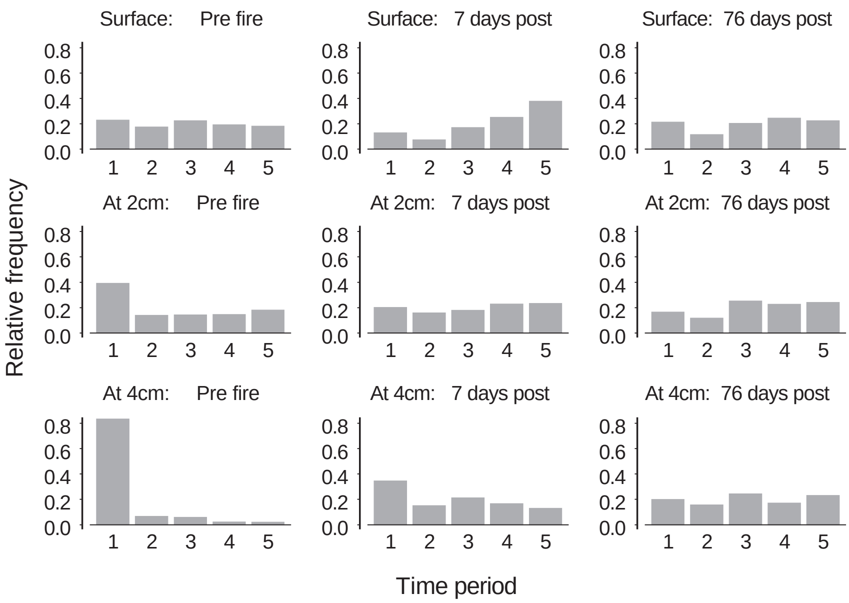

Fig. 2. Standardized estimated effects of depth (surface 0 cm, 2 cm, 4 cm) and time period (pre = pre-fire, D7 = 7-d and D76 = 76-d post-fire) on sorptivity of soil.

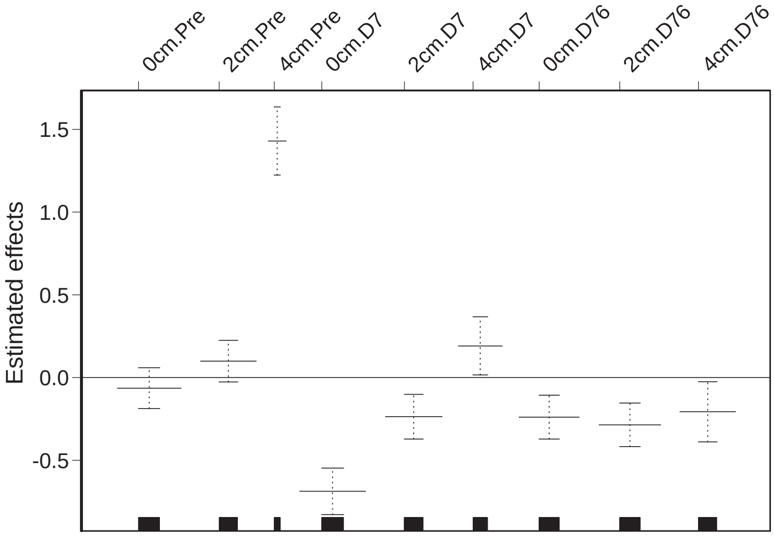

Fig. 3. Histograms showing percentage of the sampled points exhibiting various degrees of repellency at the surface and at 2 and 4 cm depths pre- and post-fire. Water repellency times were grouped into 5 cells (numbered 1, 2, 3, 4, and 5). The 5 cells represent the repellency index: (1) = 0–1 s—not repellent, (2) = 1–5 s—very low repellency, (3) = 5–30 s—low repellency, (4) = 30–180 s—moderate repellency, and (5) = >180 s—extreme repellency. The heights of the bars in the histograms represent the percentage of cases (at all locations) that fell in the corresponding group.

(Fig. 3). We observed almost no pre-fire water repellency at the 4 cm depth, where "low to no repellency" totaled 90% (Fig. 3). We believe this was partly due to pre-fire soil moisture content and the natural breakdown of water repellency since the 1960 wildfire.

Variability in WDPT between replicates within a given 15 × 15 cm site was as large as the variability seen between sites over the 1.28 ha watershed (Table 2). At the soil surface, approximately 50% of the overall variability in times of water drop penetration was due to within site variation. The percent of total variation due to within site variability seemed to decrease at lower depths (approximately 40% at 2 cm and 30% at 4 cm). In other words, there was less variability within a given site at lower depths than at the surface (Table 2). In the pre-fire soil landscape, continuous layers of hydrophobic substances are generally not formed because rodent, worm, insect, and root activity continuously disrupts the soil-column structure, and form conduits for water to enter (DeBano, 1981; Spittler, 1996). Intense and concentrated infiltration can also occur where burrow holes, tension cracks and root channels breach the repellent layer (Meyer, 1993). Additional precipitation tends to infiltrate through the existing preferential paths, as the wetted soil no longer impedes the infiltration of water (Dekker and Ritsema, 2000).

Table 2
Percent of total variation in water drop penetration time due to within site and between site variability

	Between sites	Within 15 × 15 cm area
Surface pre-fire	58.2	41.8
Surface 7-d post-fire	47.5	52.5
Surface 76-d post-fire	51.0	49.1
2 cm pre-fire	66.6	33.4
2 cm 7-d post-fire	54.6	45.4
2 cm 76-d post-fire	57.9	42.1
4 cm pre-fire	74.8	25.2
4 cm 7-d post-fire	65.1	34.9
4 cm 76-d post-fire	60.9	39.1

3.5. *Post-fire soil water repellency and spatial variation*

Seven days following the burn, "moderate to extreme repellency" at the surface had increased from 37% to 63%. Surface soils exhibiting "very low and no repellency" dropped from 41% to 20% (Fig. 3). At the 2 cm depth, 7 d post-fire "moderate and extreme repellency" increased from 33% to 46%, whereas at the 4 cm depth there was an increase of 26% from 4% to 30% (Fig. 3). At 76 d following the fire, "moderate to extreme repellency" had decreased from 63% to 47% (Fig. 3) at the surface. However, at the 4 cm depth, "moderate to extreme repellency" increased from 30% 7 d post-fire to 40% by 76 d post-fire (Fig. 3).

The 7 d post-fire increase in water repellency at all depths was due in part to downward translocation of organics released from litter and plant material and soil drying at the 2 and 4 cm depths. DeBano et al. (1970) attributed the increases in repellency at depth to volatilization of organics that moved downward along a temperature gradient and recondensed on mineral soil particles. At the 4 cm depth, the continued marginally significant decrease in rate of breakdown of repellency from 7 to 76 d post-fire was harder to explain. During the time period, no rain fell to facilitate leaching nor did any heat pulse occur that would volatilize and transport the hydrophobic compounds downward. The most likely explanation was that further soil drying due to evapotranspiration and seasonal soil temperature change at the 4 cm depth re-intensified latent soil water repellency. Dekker et al. (1998) showed that soil drying at 25 and 45 °C induced slight repellency (5–60 s), further drying at 65 °C induced slight to extreme repellency (60–3600 s), and extreme repellency (>3600 s) was caused by drying at 85 °C.

At 76 d post-burn, the histogram (Fig. 3) showed surface soil water repellency returning to near pre-fire values. No precipitation was recorded during this 76 d period, thus we do not believe soil moisture played a role in the decrease of water repellency as reported by Robichaud (1996) and Doerr and Thomas (2000). Prolonged wetting may cause clay aggregates to disaggregate and expose wettable surfaces, or cause leaching and chemical transformation of hydrophobic compounds (Burcar et al., 1994). Additionally, a soil moisture threshold at which the SDEF chaparral soils ceased to be hydrophobic is unknown, however it appeared from observation to be low.

We believe the decrease in surface water repellency over 76 d was due to physical and biological factors, primarily the movement of the unstable surface soils down the very steep slopes (>55%) due to gravity, and bioturbation by soil micro-, meso-, and macrofauna. Other mechanisms that may have contributed to the decrease in water repellency included: the growth of roots and mycorrhizal hyphae that can penetrate and disturb the water repellent layers, the decomposition and displacement of water repellent substances by microorganisms (Crockford et al., 1991), and redistribution and burial of ash. The severity of the fire may also have played a role in the duration of water repellency at the site, with areas burned at low severity recovering more quickly to pre-fire repellency levels (McNabb et al., 1989).

Variability in surface distribution of water repellency remained high throughout the watershed at both the meso-(intersite) and microscales (intrasite) following the fire. It appeared that litter depth, species composition, and species location contributed to the post-fire variability of surface soil water repellency. Differences in litter depths between species could affect the temperature and duration of the fire, and soil and fuel moistures, resulting in highly variable distributions of water repellency in the watershed (Robichaud, 1996; DeBano, 1981). In agreement with Krammes and DeBano (1965), we observed that soils located beyond the drip line, with little or no litter accumulation, exhibited "very low to no repellency". The mass and distribution of canopy fuel that collapses during the fire and smolders on the ground (secondary heating) can also cause pronounced spatial variation in total surface heating and water repellency (Odion and Davis, 2000). It is possible that the high post-fire intrasite (microscale) variation in soil water repellency was also due to the almost constant mixing and movement of different size soil particles on the steep slopes.

We observed an almost continuous movement of dry ravel immediately following the fire and throughout the dry summer months. Movement and redistribution of both fine and coarse particles on the steep sideslopes disrupted the soil surface and contributed to changes in depression microtopography, further resulting in the breakdown and redistribution of surface soil water repellency. Movement of ravel and soil downslope buried and also redistributed the post-fire ash layer across the steeper areas of the watershed. In some areas, we observed ash layers that were buried to depths of 10 cm only 2 months after the fire. Most of the buried ash layers were highly

Table 3
Analysis of deviance table for significance of various soil properties on the 'sorptivity' level of the soil

Variable	*F*-statistic	*D.F.*	*P*-value
Percent moisture	1.77	39	0.014*
Percent clay + silt	1.25	16	0.250
Soil bulk density	1.14	2.5	0.330
Location	4.45	11.7	0.000018*

Locally weighted smooth polynomials fitting procedure calculate approximate degrees of freedom which are sometimes not whole numbers.
* significant at 5% level.

wettable. Therefore, a buried lens of ash atop a water repellent layer could promote the subsurface lateral movement of water. And where this moisture encountered repellent soils, water repellency would likely be reduced.

3.6. Effects of soil physical properties and species type on soil water repellency

Of the site characteristics included in the model (soil bulk density, percent sand, percent clay, litter depth, moisture, and species type), only soil moisture and species type were found to have a significant effect on the persistence of soil water repellency at the pre-fire surface sites. Values of moisture >0.16 cm^3 cm^{-3} were observed when litter depth was high, silt and clay percentage was high, soil bulk density was low, and the species type was ceanothus. Soil moisture had a significant effect on water repellency (Table 3) when species type was not included in the model, whereas species type was significant when soil moisture was not in the model. This was probably due to the fact that soil moisture was highest under ceanothus. Soil moisture appeared to have the most significant effect on soil sorptivity. As the moisture increased from 0.08 to 0.12 cm^3 cm^{-3}, the persistence of soil water repellency also decreased. Sorptivity, or persistence in repellency, was estimated to be below average when moisture levels were less than 10% (Fig. 4). In the range of observed moisture values (0–22%), the increase in sorptivity was not linear with increasing moisture levels.

The lowest pre-fire persistence of soil water repellency was located beneath ceanothus (Fig. 5). The persistence of soil water repellency was significantly higher beneath chamise than under ceanothus (Fig. 5). However, at 7 d post-fire the persistence of repellency under ceanothus increased substantially such that no significant difference appeared to remain between soil water repellency under ceanothus and chamise (Fig. 5). All observed moisture values under ceanothus were greater than 0.16 cm^3 cm^{-3}. Because of the latter, it is hard to conclude whether the increase in sorptivity was due to the increase in soil moisture or

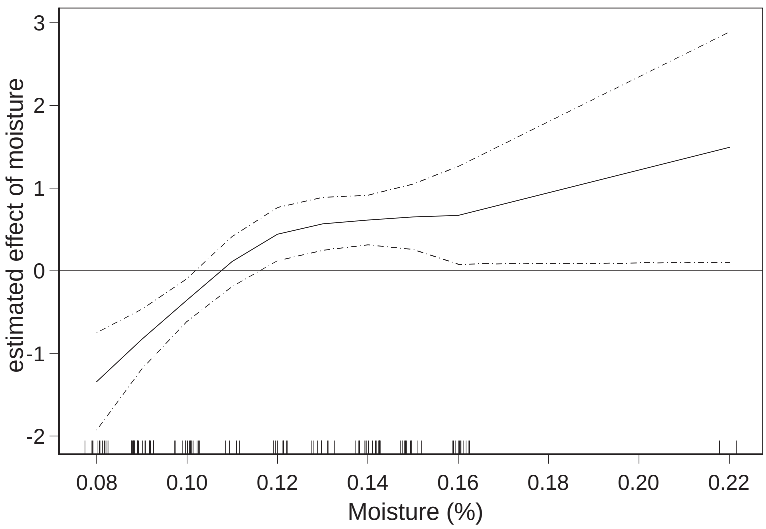

Fig. 4. Estimated partial effect of moisture on sorptivity level of soil. Hatchmarks in panels represent density of observed data points. The widths of the bars are relative to the number of observations per species group.

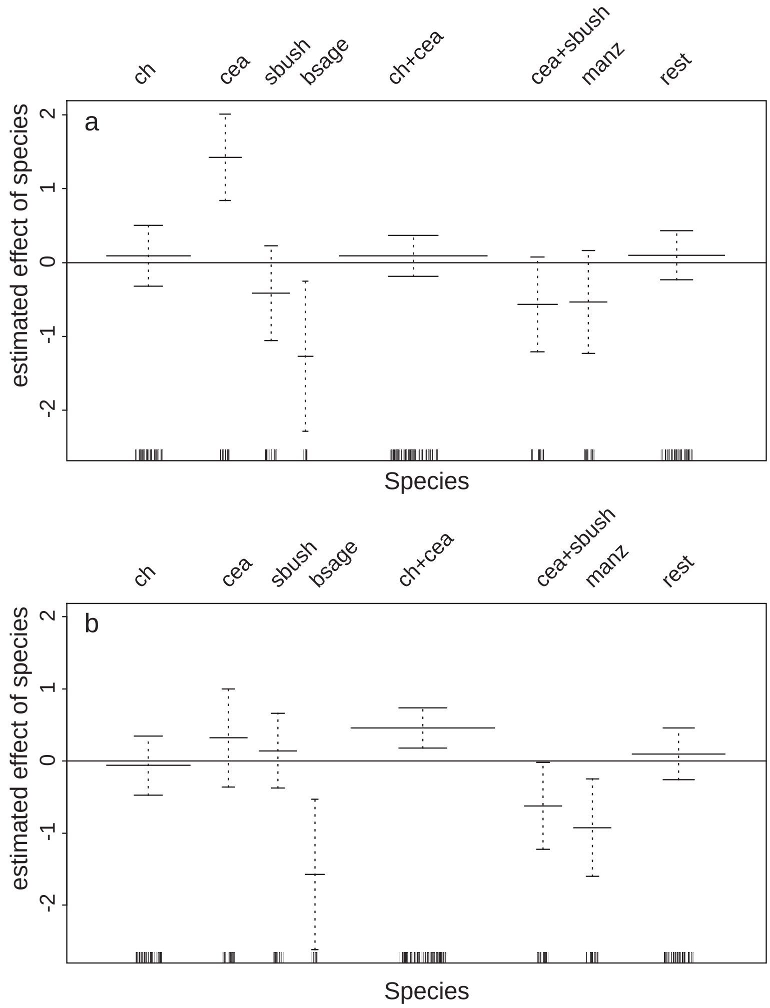

Fig. 5. (a) Pre-fire estimated 7 d effects of different species on the rate of breakdown in soil water repellency. (b) Post-fire estimated partial effects of different species on the rate of breakdown in soil water repellency. Species categories represented in panel d are chamise (ch), (ceanothus (cea), sugar bush (sbush), black sage (bsage), (chamise + ceanothus combination (ch + cea), ceanothus + sugar bush combination (ch + sbush), manzanita (manz), and three or more of any combination of the above species (rest). Hatchmarks represent density of observed data points. The widths of the bars are relative to the number of observations per species group.

some other (unmeasured) soil property that was specific to ceanothus.

The mineral soil surface beneath chamise exhibited a greater degree of pre-fire water repellency than was evidenced beneath ceanothus, even though the litter depth of chamise averaged only 19 mm as compared to 57 mm for ceanothus. The high soil moisture contents recorded in the thicker ceanothus litter layer probably resulted in greater pre-fire soil sorptivity, by decreasing the persistence of the soil water repellency. At 7 d post-fire, there was a substantial increase in soil repellency beneath ceanothus (the persistence of repellency increased), resulting in similar persistence of water repellency between ceanothus and chamise. This suggests that hydrophobic substances were released during the fire from ceanothus litter and plant material, but were not leached from living ceanothus during intervals between fires. Whereas, the pre-fire persistence of water repellency beneath chamise and other species

(Fig. 5) indicated that rain was possibly leaching water repellent organic substances out of the plants and depositing them into the soil. DeBano et al. (1970) has noted that leaf materials of chamise contain large concentrations of hydrophobic substances. We saw an overall increase in persistence of water repellency under all species categories post-fire. Since the majority of chaparral species are resprouters, the enhanced post-fire water repellency may discourage seed emergence and development, thus preventing competition for water.

Post-fire increases in soil water repellency beneath chaparral species may also result in the ponding of water. In the post-fire environment, resprouting chaparral shrubs are not affected directly by the water repellent layer, because their root systems remain intact, both above and below it. Old root channels, cracks along live roots, and other macropores can serve as penetrating points for preferential flow of the ponded water through these layers providing water to the deeper rooted chaparral species (McDonald, 1981; Meyer, 1993). Enhanced deep-water storage allows fast post-fire recovery of deeply rooted chaparral resprouters, and a competitive edge over shallow-rooted, fire following herbaceous and grass species.

We observed unidentified white to grayish fungal mats ~6–10 cm in thickness below scrub oak and sugar bush pre-fire, two species exhibiting moist, thick litter depths. Mats tended to be clustered, with the largest measured fungal area covering approximately 7 m^2. The fungal mats were located below the litter and on top and below the loose surface soil mineral horizon (0–2 cm depth). Soils with fungal mats were extremely repellent pre- and post-fire, and remained highly repellent over time and even at high soil moisture contents. Savage et al. (1969) suggested that common fungal products contribute to water repellency, especially after heating. Fire resulted in the drying and weakening of the fungal mat structure, allowing it to move with the unstable soils. This likely played a role in some increases of spatial variability of post-fire repellency at both the surface and 2 cm depths. In most cases both pre- and post-fire, we observed dry soils beneath the fungal mat areas after rain events. Due to the highly hydrophobic nature on the fungal upper surfaces, the lateral flow of water was promoted downslope.

4. Conclusions

The prescribed fire consumed the chaparral, removed the litter layer and destroyed the weak surface soil structure; leaving a thin band of ash and char on top of, and mixed in with, an unstable, granular soil of loose consistency. Median litter thickness and clay content were significantly decreased after fire while soil bulk density increased. Prior to the burn, 37% of the soil surface exhibited “moderate to extreme repellency”. After the burn, “moderate to extreme repellency” increased significantly to 63% of the soil surface. Soil water repellency at the surface returned to near pre-fire values 76 d after the burn. Because there was no rainfall during this time, we attributed this change to physical and biologic factors. Spatial variability of soil water repellency within a given 15 × 15 cm site was as large as the variability seen between sites over the 1.28 ha watershed. In this study, it seems that the distribution of soil water repellency was most strongly related to litter depth, species location and type, and soil moisture content. The increase in post-fire persistence of water repellency was largest beneath ceanothus as compared to a small increase beneath chamise. However, pre-fire persistence was higher under chamise than for ceanothus. At the 2 cm depth, 7 d post-fire increase in water repellency was likely due to volatilization and recondensation of organics moving downward on a temperature gradient. The relatively low increase in repellency with depth was a reflection of the low to moderate intensity of the burn. We saw higher sorptivity with increases in soil moisture content. Post-fire changes to soil properties may increase the hydrologic response, however the mosaic distribution of water repellency may lead to a less severe increase in hydrologic response than might be expected for a spatially more homogenous increase in repellency. Consequently, it is important that land managers understand post-fire watershed response when prescribing post-fire erosion control treatments in very steep terrain.

Acknowledgements

This work was funded by the U.S. National Fire Plan. We thank David Kerr and the Angeles National

Forest for conducting the prescribed fire. Discussions of project design and statistical interpretation with Haiganoush Preisler were very helpful. Additionally, we thank Bonni Corcoran, Lynne Casal, Joey Chong, Dave Kisor, Mike Oxford, Adrian Abordo, Jon Liao, and Valerie Oriol for field and laboratory assistance.

Appendix A

A.1. A stochastic threshold tolerance model

We allowed ξ_{ij} to be a latent (hidden) variable that described the breakdown of water repellency at location i and time t_j. The latent variable may be dependent on the properties of the soil at that location and the time a water drop has been in contact with the soil. We assumed that a water drop will infiltrate the soil by time *tj* if the latent variable, ξ_{ij}, exceeded a given threshold value C. We defined a random variable I_{ij} such that:

$$I_{ij} = 1 \qquad \text{if } \xi_{ij} > C$$

$$= 0 \qquad \text{otherwise}$$

where $\xi_{ij} = \mu_{ij} + \varepsilon_{ij}$; the function μ_{ij} is a deterministic function of location and time; and ε_{ij} are independent error terms due to the random variability between sites that are not accounted for by the observed soil properties. Furthermore, we assumed that the latent variable [from the time the water drop touches the soil and for the duration of the experiment (180 s)], is increasing at a fixed rate λ_i. Then $\mu_{ij} = \lambda_i \tau_j$, where τ is some function of time. For example, in Philip's equation for water infiltration (Philip, 1969), $I = St^{0.5} + At$, where I stands for infiltration, S is sorptivity, and A corresponds to the gravitational force. The latent variable, μ_{ij}, maybe related to the Philip's equation if $\tau = t^{0.5}$ and λ_i is the sorptivity of the soil at location i. The second term in Philip's equation, corresponding to the gravitational forces, was assumed to be negligible because the sorptive forces mostly govern the initial phase of water infiltration. We note that in our model, the rate of breakdown, λ, is assumed to be fixed over the duration of the experiment but allowed to vary between location (i.e., λ is a function of location but not time). Finally, we assumed that ε_{ij} follows the Weibull distribution with scale and shape parameters b, and c respectively. This led to the following statement for the probability, p_{ij}, of a water drop infiltrating the soil at location i and by time t_j

$$Pr\left[I_{ij} = 1\right] = \pi_{ij} = 1 - \exp\left(-\exp\left\{c\left[\log(\tau_j) + \log(\lambda_i) - \log(b)\right]\right\}\right). \qquad \text{(A1)}$$

Additionally, the conditional probability, q_{ij}, of a water drop infiltrating the soil by time t_j, given that the drop had not infiltrated the soil by time t_{j-1} (with $t_{j-1} < t_j$) is

$$\frac{\pi_{ij} - \pi_{i(j-1)}}{1 - \pi_{i(j-1)}} = q_{ij} = 1 - \exp\left(-\exp\left\{\gamma_j + c\log(\lambda_i) - c\log(b)\right\}\right) \qquad \text{(A2)}$$

where γ_j is such that $\tau_j^c = e^{\gamma_1} + e^{\gamma_2} + \cdots + e^{\gamma_j}$. Further details may be found in Barlett (1978) and Preisler et al. (1999).

The next section will describe how the conditional probabilities in Eq. (A2) together with the WDPT data may be used to estimate τ as a function of time and estimate the sorptivity parameter, λ_i, as a function of selected soil and site physical properties.

A.2. Estimation of model parameters

We allowed n_{ik} ($k = 1, 2, 3, 4$) to be the cumulative number of drops, out of 20, that had infiltrated the soil at site i by 1, 5, 30, and 180 s respectively. We allowed r_{ik} ($k = 1, 2, 3, 4$) to be the number of drops that infiltrated the soil in the intervals (0,1] s, (1,5] s, (5,30] s, and (30,180] s, respectively. Then r_{ik} ($k = 1,2,3,4$) are independent binomial variables with $n = 20 - n_{i(k-1)}$ and probability of response, q_{ij}, given by Eq. (A2) above. Note that $n_{i0} = 0$.

We estimated the effects of soil properties on the rate of breakdown of soil repellency by inputting the observed number of drops, r_1, r_2, r_3, r_4, in the four classification groups into the S-Plus statistical package (S-PLUS, 2001). We used the binomial distribution with the complementary log–log option and the linear predictor

$$\log\left(-\log\left(1 - q_{ij}\right)\right) = \alpha + \gamma_j + \beta_i \qquad \text{(A3)}$$

where γ_j is a categorical variable corresponding to the 4 classification classes (γ_j describes the temporal component of the latent variable, i.e., τ). The parameter β_i describes the spatial component of the latent variable and was modeled by the sum of smooth functions of the explanatory variables, namely, the soil physical properties at location i. Using the notation in Eq. (A2) the function β_i is seen to be proportional to the logarithm of the rate parameter λ_i. Consequently, studying the effects of site characteristics on β_i is equivalent to studying the effects on the sorptivity at location i.

References

Barlett, N.R., 1978. A survival model for a wood preservative trial. Biometrics 34, 673–679.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis: Part 1. Physical and Mineralogical Properties, 2nd ed. American Society of Agronomy, Madison, WI, pp. 363–375.

Burcar, S., Miller, W.W., Tyler, S.W, Johnson, D.W., 1994. Seasonal preferential flow in two Sierra Nevada soils under forested and meadow cover. Soil Science Society of America Journal 58, 1555–1561.

Cleveland, W.S., Gross, E., Shyu, W.M., 1992. Local regression models. In: Chambers, J.M., Hastie, T.J. (Eds.), Statistical Analysis in S. Wadsworth, Pacific Grove, CA, pp. 309–376.

Crockford, S., Topadilis, S., Richardson, D.P., 1991. Water repellency in a dry slerophyll forest: measurements and processes. Hydrological Processes 5, 405–420.

Danielson, R.E., and Sutherland, P.L. 1986. Porosity. In: Klute, A. (Ed.) Methods of Soil Analysis: Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 443–461.

DeBano, L.F., 1981. Water repellent soils: a state-of-the-art. USDA Forest Service General Technical Report PSW-46Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

DeBano, L.F., Mann, L.D., Hamilton, D.A., 1970. Translocation of hydrophobic substances into soils by burning organic litter. Soil Science Society of America Journal 31, 130–133.

DeBano, L.F., Rice, R.M., Conrad, C.E., 1979. Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff. USDA Forest Service Research Paper PSW-145. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Dekker, L.W., Ritsema, C.J., 2000. Wetting patterns and moisture variability in water repellent Dutch soils. Journal of Hydrology 231–232, 148–164.

Dekker, L.W., Ritsema, C.J., Oostindie, K., Boersma, O.H., 1998. Effect of drying temperature on the severity of soil water repellency. Soil Science 163, 780–796.

Doerr, S.H., Thomas, A.D., 2000. The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. Journal of Hydrology 231–232, 134–147.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 1998. Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. Soil Science 163, 313–324.

Dunn, P.H., Wells II, W.G., Dickey, J., Wohlgemuth, P.M., 1982. Role of fungi in post-fire stabilization of chaparral ash beds. USDA Forest Service General Technical Report PSW-58. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, pp. 378–381.

Dunn, P.H., Barro, S.C., Wells, W.G., Poth, M.A., Wohlgemuth, P.M., Colver, C.G., 1988. The San Dimas Experimental Forest: 50 years of research. USDA Forest Service General Technical Report PSW-104. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Duriscoe, D.M., Wells II, W.G., 1982. Effects of fire on certain physical properties of selected chaparral soils. In: Conrad, C.E., Oechel, W.C. (Eds.), Proceedings. Symposium, Dynamics and Management of Mediterranean-type Ecosystems. USDA Forest Service General Technical Report PSW-58. Pacific Southwest Forest and Range and Experiment Station, Berkeley, CA, p. 594.

Gardner, W.H. 1986. Water content. In: Klute, A. (Ed.) Methods of Soil Analysis: Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 493-544.

Gee, G.W., Bauder, J.W. 1986. Particle-size analysis. In: Klute, A. (Ed.) Methods of Soil Analysis: Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 383-411.

Giovannini, G., Lucchesi, S., Giachetti, M., 1988. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Science 146, 255–261.

Graham, R.C., Herbert, B.E., Ervin, J.O., 1988. Mineralogy and incipient pedogenesis of Entisols in anorthosite terrane of the San Gabriel Mountains, California. Soil Science Society of America Journal 52, 738–746.

Hanes, T.L. 1974. The vegetation called chaparral. In: Rosenthal, M. (Ed.) Symposium on Living with the Chaparral. University of California, Riverside, 1973. Sierra Club, California Division of Forestry, USDA Forest Service, pp. 1-5.

Hellmers, H., Horton, J.S., Juhren, G., O'Keefe, J., 1955. Root systems of some chaparral plants in southern California. Ecology 36, 667–678.

Kaluzny, S.P., 1997. S+SpatialStats: User's Manual for Windows and UNIX. Springer, New York.

Keeley, J.E., Keeley, S.C., 1987. Role of fire in the germination of chaparral herbs and suffrutescents. Madrono 34, 240–249.

Keeley, J.E., Fotheringham, C.J., Morais, M., 2000. Reexamining fire suppression impacts on brushland fire regimes. Science 284, 1829–1831.

Kittredge, J., 1955. Litter and forest floor of the chaparral in parts of the San Dimas Experimental Forest, California. Hilgardia 23, 563–596.

Krammes, J.S., DeBano, L.F., 1965. Soil wettability: a neglected factor in watershed management. Water Resources Research 1, 283–286.

Lehman, E.L., 1959. Testing Statistical Hypotheses. Wiley & Sons, New York. 369 pp.

McDonald, P.M., 1981. Adaptations of woody shrubs. Presented at a Workshop on Reforestation of Skeletal Soils in Southwest Oregon, Nov.18–19. Medford Press, Oregon.

McNabb, D.H., Gawed, A.F., Froehlich, H.A., 1989. Infiltration, water repellency, and soil moisture content after broadcast burning a forest site in southwest Oregon. Journal of Soil and Water Conservation 44, 87–90.

Meyer, G.A. 1993. Holocene and modern geomorphic response to forest fires and climate change in Yellowstone National Park. Ph.D. Dissertation, University of New Mexico, Albuquerque, NM.

Miller, M. 2001. Fire behaviour and characteristics. Fire effects guide NFES 2394, National Wildfire Coordinating Group, National Interagency Fire Center, Boise, ID.

Nourse, J., 1998. Digital geologic map of the Glendora 7.5' quadrangle, Los Angeles County, California. Open File Report, vol. XXX-98. U.S. Geological Survey, Riverside, CA [Rept #??].

Odion, D.C., Davis, F.W., 2000. Fire, soil heating, and the formation of vegetation patterns in chaparral. Ecological Monographs 70. , 149–169.

Philip, J.R., 1969. The theory of infiltration. Advances in Hydroscience 5. , 215–296.

Preisler, H.K., Robertson, kJ.L., Hoover, K., McCutchen, B.F., 1999. Statistical methods to assessing responses over time in bioassays with mixtures. Journal of Economic Entomology 92 (3), 598–603.

Radtke, K.W.H., 1981. An urban viewpoint of wildland fire problems. Proceedings of the convention of the Society of American Foresters, pp. 117–122.

Ritsema, C.J., Dekker, L.W., 1994. How water moves in a water-repellent sandy soil: 2. Dynamics of fingered flow. Water Resources Research 30. , 2519–2531.

Robichaud, P.R., 1996. Spatially-varied erosion potential from harvested hillslopes after prescribed fire in the Interior Northwest. University of Idaho, Moscow, ID. 219 p. Ph.D. dissertation.

Robichaud, P.R., Miller, S.M., 1999. Spatial interpolation and simulation of post-burn duff thickness after prescribed fire. International Journal of Wildland Fire 9, 137–143.

Ryan, T.M., 1991. Soil Survey of Angeles National Forest Area, California, vol. 588-137. USDA Forest Service, Glendora, CA.

S-PLUS, 2001. S-PLUS 6 for Windows Guide to Statistics, vols. 1–2. Insightful Corporation, Seattle, WA.

Savage, S.M., Martin, J.P., Letey, J., 1969. Contribution of some soil fungi to natural and heat-induced water repellency in sand. Proceedings-Soil Science Society of America 33, 405–409.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.C., 1998. Field book for describing and sampling soils. Version 1.1. USDA-NRCS-NSSC. Lincoln, NE.

Sinclair, J.D., 1953. Erosion in the San Gabriel Mountains of California. Eos, Transactions, vol. 35. American Geophysical Union, pp. 264–268.

Soil Survey Laboratory Staff, 1992. Soil survey laboratory methods manual. Version 2.0 USDA-SCS. Soil Survey Investigation Report 42. U.S. Govt. Print. Off., Washington, DC.

Soil Survey Division Staff, 1993. Soil survey manual. USDA Agricultural Handbook, vol. 18. U.S. Govt. Print. Off., Washington, DC.

Spittler, T.E., 1996. Fire and the debris-flow potential of winter storms. Proceedings of the Symposium of Brush Fires in California Wildlands, Ecology and Resource Management. International Association of Wildland Fire, Fairfax, VA.

Story, H.C., 1948. Geology of the San Gabriel Mountains, California, and its relation to water distribution. California Natural Resources. Division Forestry, CA, pp. 1–19.

Teramura, H.A., 1980. Relationships between stand age and water-repellency of chaparral soils. Bulletin of the Torrey Botanical Club 104, 42–46.

Ulery, A.L., Graham, R.C., 1993. Forest fire effects on soil color and texture. Soil Science Society of America Journal 57, 135–140.

Vincent, K.R., Chadwick, O.A., 1994. Synthesizing bulk density for soils with abundant rock fragments. Soil Science Society of America Journal 58, 455–464.

Welling, R., Singer, M., Dunn, P., 1984. Effects of fire on shrubland soils. In: de Vries, J.J. (Ed.), Proceedings of the Chaparral Ecosystems Research Conference. Water Resources Center-University of California, Davis, pp. 42–50. Report No. 62.

Wells, C.G., Campbell, R.E., DeBano, L.F., Lewis, C.E., Fredriksen, R.L., Franklin, E.C., Froelich, R.C., Dunn, P.H., 1979. Effects of Fire on Soil: A State of Knowledge Review. USDA Forest Service General Technical Report WO-7. U.S. Govt. Print. Off., Washington, DC.